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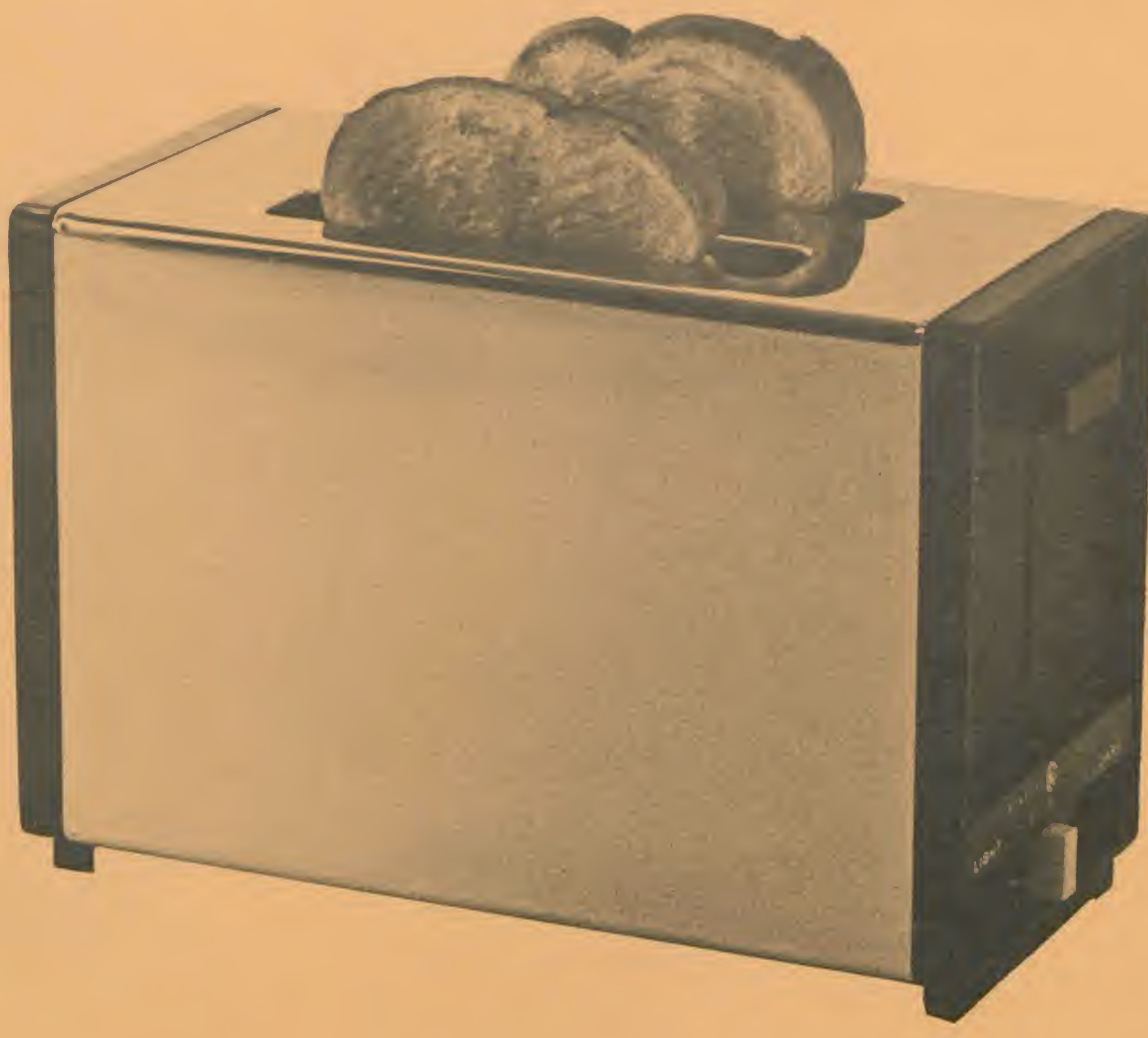

THE TOASTER

Heat and Energy Transformations.

THE TOASTER

A Module on Heat and Energy Transformations

SUNY at Binghamton

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The Toaster

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3 4 5 6 7 8 9 0 E B E B 7 8 3 2 1 0 9 8 7 6

TABLE OF CONTENTS

THE TOASTER

ABOUT THIS MODULE

In our technological society there are many devices which use electricity for heating processes. You are probably most familiar with those which appear in the home, such as irons, water heaters, clothes dryers, hair dryers, coffee makers, ranges, and toasters. Although you may be less familiar with them, devices based on the same properties are common items in industrial manufacturing plants and research laboratories.

This module introduces the principles needed to understand the operation of such devices. We have chosen to use the toaster as an example. As you work through the module, you should try to reach the following goals:

1. Learn about processes that change electrical energy into heat.
2. Learn to identify the major forms of energy and to describe how one form changes into another.
3. Discover that materials expand when heated and use a formula that describes this effect.
4. Learn to describe one or two systems which are controlled by a thermal expansion device.

This list of goals should give you a general idea of the topics included in the module. More specific statements on what you will be expected to know and be able to do may be obtained from your teacher.

INTRODUCTION

The toaster is a simple device to operate: you plug it in, put in the bread, push down the lever, and in a short time up pops the toast.

There are several interesting things about the principles of operation of the toaster. The main feature is that the toaster produces heat by using electricity. This is an example of a general process we see many times every day: energy changing from one form to another. This process and the laws of nature which control it are of such great importance that we shall look at them in some detail.

Energy is the capacity to do work. Since we have defined one scientific word, energy, in terms of another, work, we must be certain that we know the meaning of the word "work." If you push a hand lawnmower across the lawn, you do work. If you raise a book from the floor to a table top, you do work. The amount of work done by a force *acting in the direction of the motion* is equal to the force multiplied by the distance moved. A person (or an object) has energy if he or she (or it) can do work. One way to grasp the meaning of energy is to consider the various forms in which it appears.

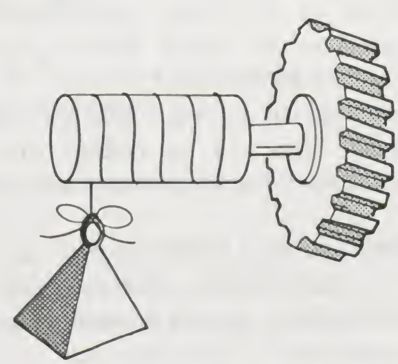


Figure 1. As the weight falls it runs machinery which does work.

Forms of Energy

One form of energy results from the ability of an object which is raised up to do work. In general, an object in a higher position can do work while moving to a lower position. This type of energy, which is associated with the *potential* to do work as a result of

the *gravitational force*, is called *gravitational potential energy.*

Another common form of energy is the result of forces produced in stretching, compressing, bending, or twisting materials. Such forces are called elastic forces.

The *potential* to do work as a result of *elastic forces* is called *elastic potential energy.* Consider this example of elastic energy. When you lower the mechanism which carries the bread into the toaster, you compress a spring. Later, the elastic potential energy of the compressed spring does the work of "popping up" the toast.

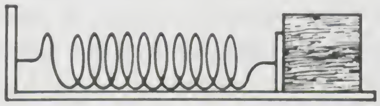


Figure 2. A compressed spring can move objects, thereby doing work.

If you have ever driven a nail with a hammer, you have used another form of energy, called *kinetic energy.* The *work* which can be done by a *moving object* in being brought to rest is called *kinetic energy.* ("Kinetic" refers to motion.)

We distinguish between the two types illustrated in Figure 3 by calling the first *translational* and the second *rotational* kinetic energy.

In other words, if the motion is from one place to another, it is called *translational;* and if it is a turning motion around an axis, it is called *rotational.*

A form of energy which may not be as familiar as the ones already mentioned is the energy associated with electricity. The energy associated with *charged particles* at rest or in motion is called *electromagnetic energy.* In everyday life, this energy is most often used in devices which have charged particles moving through wires. This kind of energy is often just called *electrical energy.* Examples include the energy required to operate the toaster, electric motors, and electric lights, as in Figure 4A and B.

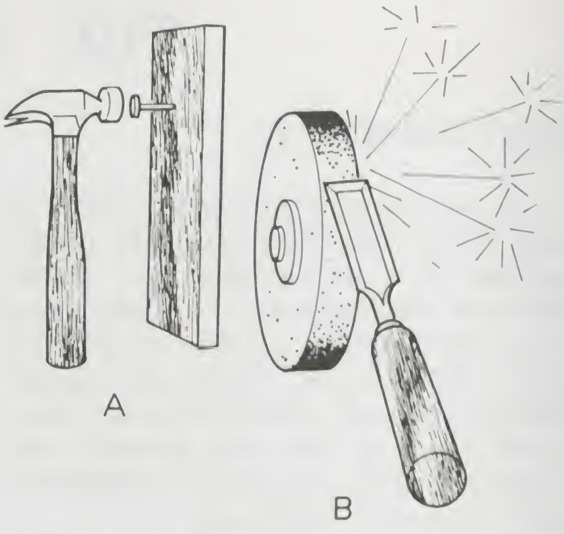


Figure 3A. The hammer does work as it drives the nail into the wood.
Figure 3B. The grinding wheel does work as the wheel slows down, even after the power is shut off.

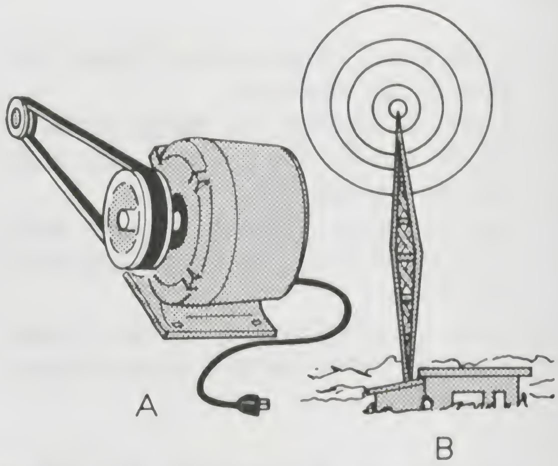


Figure 4A. Electricity runs the motor, which does work.
Figure 4B. Radio waves are capable of doing work.

Charges at rest sometimes contain a form of electromagnetic energy called *electrostatic potential energy.* If you rub a balloon on your hair on a dry day, the balloon can lift your hair, or other small objects, and thus do work. Moving storm clouds also become charged and develop the potential to deliver large amounts of energy in the form of lightning bolts. The sudden light and sound is caused by a huge

electric current, and it is an example of electrical energy which results in work being done (although this isn't a very useful kind of work). But even before the lightning strikes, the cloud has the capacity to deliver work, so we say it has electrostatic potential energy.

Electromagnetic energy also appears in the form of *electromagnetic radiation.* This includes radio and TV waves, light, X-rays, and gamma rays (a gamma ray is produced by nuclear effects).

A form of energy which keeps us warm and does a variety of other things for us is called *heat energy* or *thermal energy*. The steam engine is run by thermal energy; see Figure 5. *Heat* is the energy which is *transferred* from one object to another because of a *temperature difference.* Heat is usually involved in such processes as raising the temperature of an object, melting, and boiling.

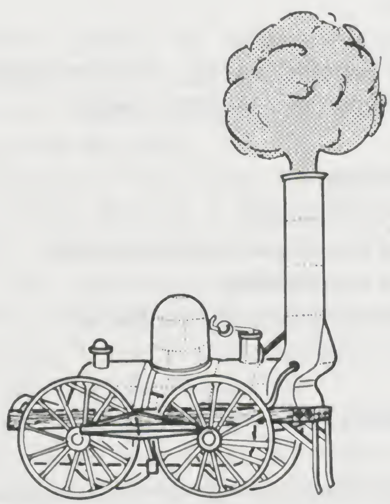


Figure 5. Thermal energy runs the steam engine.

As you read and turn these pages, you are using a form of energy called chemical energy. *Chemical energy* is involved in all processes in which the atoms are rearranged to form *different substances* (chemical reactions). Examples of such reactions include burning, the production of electrical energy in a battery, and the production in a muscle of the energy needed to turn a crank as in Figure 6.

Figure 6. The work done by the woman comes from the chemical energy in the food she ate.

The most recent form of energy to be used by man is *nuclear energy.* The energy which comes from the core, or *nucleus,* of the atom is called *nuclear energy.*

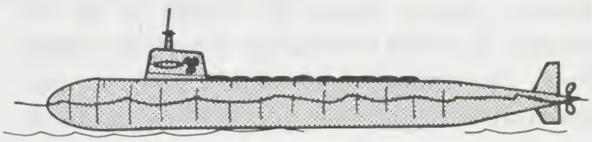


Figure 7. Nuclear energy is changed to thermal energy and the thermal energy powers the submarine.

SUMMARY

In summary, we identify the following forms of energy:

I. Mechanical energy

- (a) Gravitational potential energy
- (b) Elastic potential energy
- (c) Kinetic energy (both rotational and translational)

II. Electromagnetic energy

- (a) Electrical energy
- (b) Electrostatic potential energy
- (c) Electromagnetic radiation

III. Heat energy

IV. Chemical energy

V. Nuclear energy

TRANSFORMATIONS OF ENERGY

It is possible to think of many different processes which involve changes from one kind to another among the different types of energy. For example, when using nuclear energy, heat is produced before the work is done. The main feature of the toaster is the changing of electrical energy to heat.

Let's look at some other situations which involve energy transformations.

As a yo-yo unwinds, it drops lower, thus losing gravitational potential energy. But as it moves down, it goes faster; therefore, the kinetic energy increases. Thus we have an example of the change of gravitational potential energy into translational and rotational kinetic energy. When the string is all unwound, it starts rewinding; the yo-yo climbs back up, transforming kinetic energy into gravitational potential energy. See Figure 8.

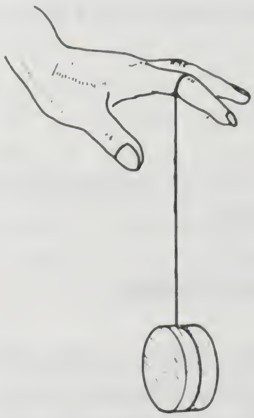


Figure 8. The yo-yo.

You will find a clever example of energy transformation in the pop-up mechanism on some toasters. When you push down the handle to lower the elevator mechanism, it compresses a spring. When the toast is done, the elevator is released and the elastic potential energy of the spring is changed into other forms. Some goes into gravitational potential energy of the elevator and toast. Some goes into kinetic energy of the elevator and toast.

A difficulty appears when designing the elevator. If the spring is made strong enough to lift the heaviest slices of bread, it will be so strong it will throw the lightest slices into your corn flakes. When you examine the toaster in the laboratory, you will see how this problem is solved by causing some of the elastic potential energy to go into rotational kinetic energy.

In almost all processes involving energy transformation, some heat is produced whether you want it or not. In the two cases just discussed, the yo-yo and the toaster elevator, the rubbing of one surface on another produces heat energy (but not much). As another example, an electric motor gets warm while running because of friction in the bearings and because of resistance in the wires. This is wasted energy, so we try to keep it as small as possible. Figure 9 shows some other examples of energy transformation.

Question.

Discuss the energy transformations in the following devices or processes:

1. a flashlight
2. a wind-up clock
3. a car moving at constant speed
4. a car accelerating
5. a football thrown into the air

CONSERVATION OF ENERGY

Throughout the preceding discussion of energy transformations, we have hinted at an idea: *energy cannot be created or destroyed*, although its form may be changed. This is a very basic law of nature and is called the *law of conservation of energy.*

In order to proceed with a meaningful discussion of the law, we must state how to assign numbers to various forms of energy. Descriptive terms are not enough; we need numbers. Although it is possible to do this for all the various forms of energy, we will concentrate on the two forms of most importance in the toaster: electrical energy and thermal energy.

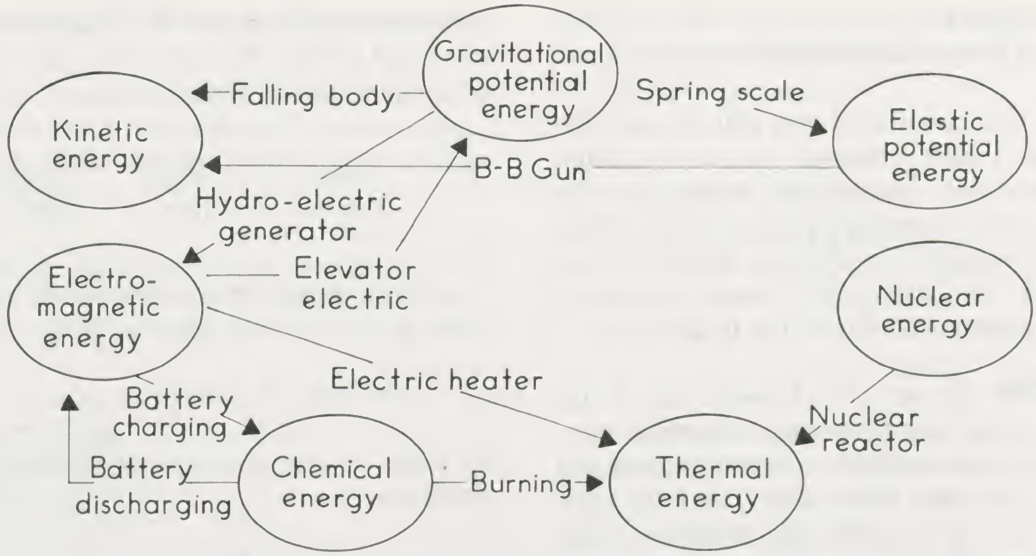


Figure 9. A few of the many different energy transformations.

ELECTRICAL ENERGY*

The amount of electrical energy delivered to or by a circuit element is determined by three things: the current, the voltage, and the time.

Current is the rate at which electric charge flows through a circuit. The common unit for current is the ampere. The device used for measuring current is called an ammeter. (The name "ammeter" comes from "ampmeter," but for some strange reason the "p" is left out.) See Figure 10.

The *voltage* between two points in an electric circuit is equal to the work done per unit charge as the charge moves from the first point to the second. Saying it another way, for simple circuit elements like heating coils, a larger voltage across the element causes a larger current to flow. The unit of voltage is the volt; an instrument that measures voltage is called a voltmeter.

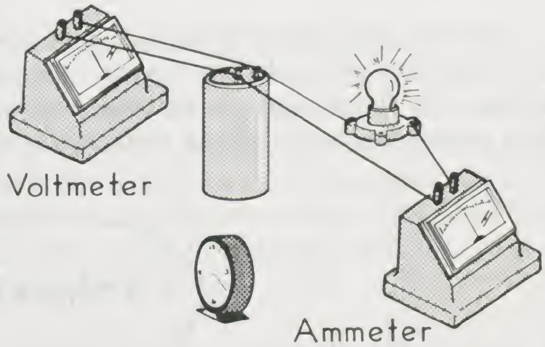


Figure 10.

The work that charges (electrons) do when they move through the wires of a toaster is to bump into atoms of the metal wire and cause them to vibrate. The energy of the vibrating atoms is the same energy we previously called heat energy or thermal energy. If a certain unit of charge produces two calories of heat energy when it flows through a resistor, and if three such units flow through the resistor every second, then the heat energy produced is six calories per second. (The calorie is a unit of heat. It will be defined later.)

*This treatment of electricity is valid for all direct current circuits and for many alternating current devices, including the toaster. It doesn't work for electric motors which run on alternating current.

EXPERIMENT 1.
Electrical Power–Immersion Heater

In this experiment you will measure the electrical power delivered to an immersion heater and will compare the measured value with the manufacturer's rating for the device.

To simplify the wiring, a transfer box is provided. The immersion heater, voltmeter, and ammeter are all connected to this box.

CAUTION: Be sure the transfer box is not plugged in when you make your connections. Your instructor will plug it in after checking your circuit. Place the heater in a cup of water before closing the circuit; it will burn out if provided with power when not in water. Complete the connections and ask your instructor to check the circuit.

Record the meter readings, which give you measurements of the current passing through the heater and the voltage across it, then unplug the heater. Since voltage is work per unit charge and the current is rate of flow of charge (charge per unit time), the product of the two is work per unit time:

$$\frac{\text{Work}}{\text{Charge}} \times \frac{\text{charge}}{\text{time}} = \frac{\text{work}}{\text{time}}$$

The rate of doing work (work per unit time) is called power. Thus we have:

$$\text{Voltage} \times \text{current} = \text{power}$$

In terms of the common symbols for these quantities,

$$VI = P$$

If the voltage is expressed in volts and the current in amperes, then the power is in units called *watts*; one watt (W) equals one volt ampere. To give you some feeling for the size of a watt, a person running up a flight of stairs uses about 500 watts of power.

Compute the power. Does it agree with the rated power stamped on the heater?

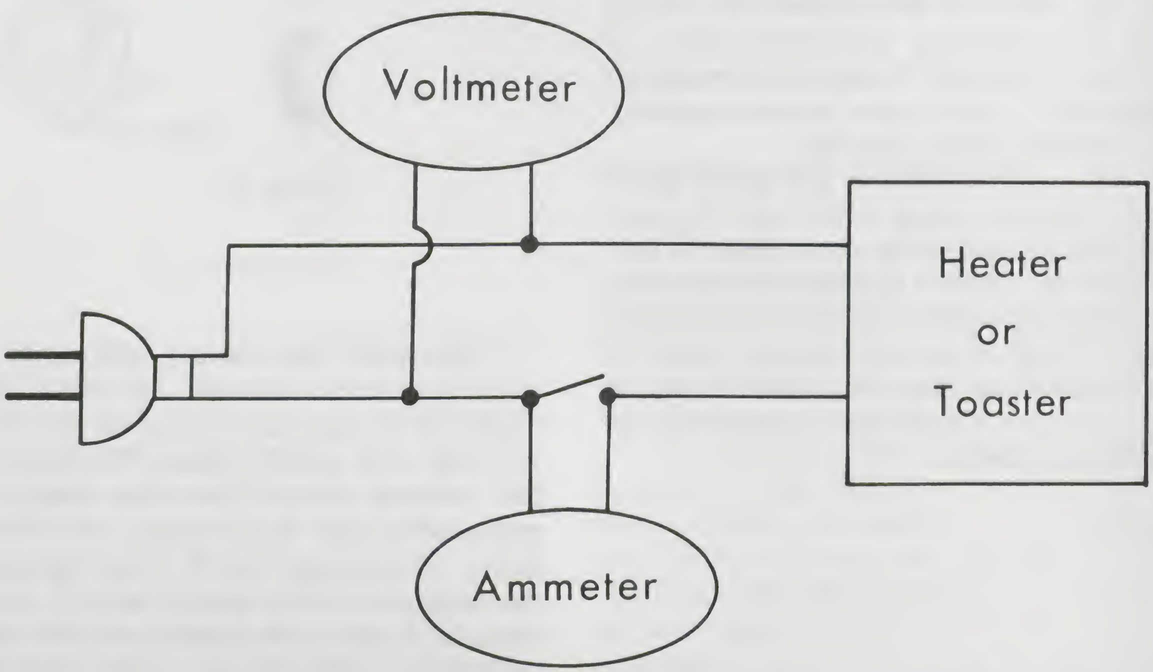


Figure 11. The transfer box. The ammeter is wired into the line so that the current passes through it to get to the toaster. The voltmeter is wired across the line, and it measures the line voltage.

EXPERIMENT 2. Electrical Power—Toaster

Use the procedure of Experiment 1 to determine the power delivered to the toaster. Compare your answer with the manufacturer's rating.

Example 1. Find the power provided by a 6-volt (6 V) battery to a circuit drawing 2 amperes (2 A) of current.

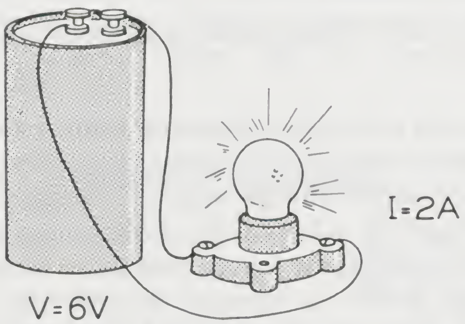


Figure 12.

Solution:

$$P = VI$$

$$= (6\ \text{V}) \times (2\ \text{A})$$

$$= 12\ \text{W}$$

Example 2. A light bulb is stamped "40 watts, 120 volts." How much current will it draw when connected to a 120-V line?

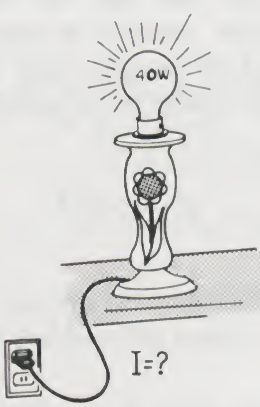


Figure 13.

Solution: In this case the power and voltage are known, and it is necessary to solve for current.

$$\begin{aligned} P &= IV \\ I &= P/V \\ &= 40\ \text{W}/120\ \text{V} \\ &= 40\ \text{V}\cdot\text{A}/120\ \text{V} \\ &= 1/3\ \text{A} \end{aligned}$$

In many cases we will be interested not in the rate at which work is being done, but rather the total amount of work done during some period of time. Since power is the rate at which work is done, just multiply by time to get the total work, or energy:

$$W = Pt$$

$$= VIt$$

If the power is in watts and the time in seconds, then the work or energy is in watt-seconds. This combination of units appears so often we give it a name of its own; *joule* (J). That is, a joule is a watt-second. To give you a feeling for the size of the joule, it is approximately the energy needed to lift a hamburger three feet.

Example 3. How much electrical energy is converted to heat and light if a 100-watt light bulb is left on for one hour?

Solution:

$$\begin{aligned} W &= Pt \\ &= 100\ \text{W}\cdot 1\ \text{h} \\ &= 100\ \text{W}\cdot 3600\ \text{s} \\ &= 360{,}000\ \text{J} \end{aligned}$$

Although the joule is the unit of work and energy preferred by scientists, a more commonly used unit when dealing with electricity is the *kilowatt hour,* abbreviated *kWh.* One kWh is the energy produced by a 1000-watt (one kilowatt) source in one hour. This is approximately the energy needed to

lift a car to the top of the Empire State Building. The conversion between kilowatt hours and joules is easily established:

$$\begin{aligned} 1 \text{ kilowatt hour} &= 1000 \text{ watt hours} \\ &= 1000 \text{ watt } (3600 \text{ seconds}) \\ &= 3.6 \times 10^6 \text{ watt seconds} \\ &= 3.6 \times 10^6 \text{ joules} \end{aligned}$$

In circuit problems, it is often convenient to compute the energy directly in units of kilowatt hour. This rather large amount of energy (1 kWh) costs three or four cents when we buy it in the form of electricity in our homes.

Example 4. How much energy is required to make a slice of toast? The toaster is rated at 1200 watts, and the toasting time is about one minute. Express the answer in kilowatt hours.

Solution:

$$\begin{aligned} W &= Pt \\ &= (1200 \text{ W}) \times (1 \text{ min}) \\ &= (1.2 \text{ kW}) \times (1/60 \text{ h}) \\ &= 0.02 \text{ kWh} \end{aligned}$$

Example 5. If electricity costs 2 cents per kilowatt hour, for how many hours will 50 cents run a 1000-watt space heater?

Solution: At 2 cents per kilowatt hour, 50 cents will buy 25 kilowatt hours. Knowing the number of kilowatt hours we can solve for the time:

$$W = Pt$$

$$t = W/P = \frac{25 \text{ kWh}}{1 \text{ kW}} = 25 \text{ h}$$

THERMAL ENERGY

Raising the temperature of an object by rubbing it is a simple experiment which shows that work and heat are related. In fact, it was just this type of experiment which led to the identification of heat as a form of energy.

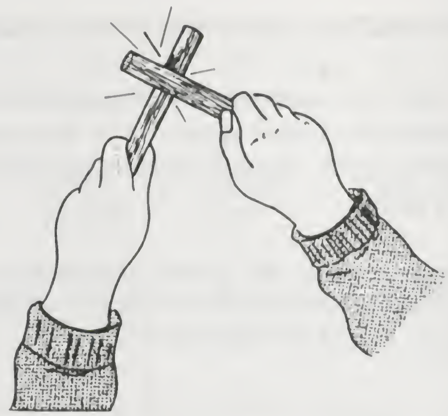


Figure 14. Rubbing causes a temperature rise.

Near the end of the eighteenth century Count Rumford noticed that during the drilling of a cannon barrel, enough heat to boil water was produced for as long as the drilling continued. Later experiments proved that other forms of energy could be changed to heat and vice versa. These observations led to the statement of the basic law of conservation of energy.

However, long before it was realized that heat is a form of energy, scientists had studied the effects of heat on such things as temperature, melting, and boiling. To explain their observations they assumed that a substance, which they called "caloric," flowed from one object to another during heating processes. Although we no longer believe the caloric theory, a souvenir remains in the name for a unit of thermal energy, the *calorie*. A calorie is the heat required to raise the temperature of one gram of water one centigrade degree.

If heat is applied to a sample of material, its temperature will rise. We find that the amount of heat required is proportional to the mass (m) of material and also proportional to the change in temperature (ΔT)*. That is,

$$Q = cm\Delta T$$

where Q is the amount of heat and c is a constant for a given material but has different

*The symbol Δ, which is the Greek letter *delta*, indicates the change in a quantity.

values for different materials. The constant c is called the *specific heat*.

From the definition of a calorie, the specific heat of water is one calorie per gram and per centigrade degree (C°). If the specific heat of a substance is known, the amount of heat required to increase the temperature of a given mass of the material a given amount can be determined.

Table I lists the experimentally determined values of specific heat for several common substances. (The values are the same in both the metric system of units and in the British system which will be described shortly.)

TABLE I. Specific Heat

	cal/g C° or Btu/lb F°
Aluminum	0.215
Bakelite	0.55
Copper	0.092
Glass	0.20
Iron	0.113
Lead	0.030
Water	1.00

Example 6. How much heat is required to raise the temperature of 5 kilograms of iron 6 centigrade degrees?

Solution: Consulting the table above we find that the specific heat of iron turns out to be 0.113 cal/gC°.

$$Q = cm\Delta T$$

$$= (0.113 \text{ cal/gC°}) \times (5000 \text{ g}) \times (6 \text{ C°})$$

$$= 3390 \text{ cal}$$

Note that in using the formula above, $Q = cm\Delta T$, m is such that Q has units of calories. Some scientists prefer to express m in kilograms and this will result in a value for Q expressed in kilocalories. This unit for energy, the kilocalorie, is the same amount of usable energy contained by food when a dietician says the food contains one calorie. To say it another way, the "dietary calorie" is really a kilocalorie.

Another heat unit frequently used in English speaking countries is the *British thermal unit*, abbreviated Btu. One Btu is the amount of heat required to raise the temperature of one pound of water one Fahrenheit degree.

Calories and Btu's are different units for the same quantity, energy, so they must be related by a conversion factor. And both can be related to the units for energy introduced earlier, joules and kilowatt hours. The conversion factors for these energy units are given in Table II.

TABLE II.

Conversion Factors

one J $= 2.78 \times 10^{-7}$ kWh
$= 0.239$ cal
$= 9.48 \times 10^{-4}$ Btu

one kWh $= 3.60 \times 10^{6}$ J
$= 8.60 \times 10^{5}$ cal
$= 3.41 \times 10^{3}$ Btu

one cal $= 1.16 \times 10^{-6}$ kWh
$= 4.18$ J
$= 3.97 \times 10^{-3}$ Btu

one Btu $= 252$ cal
$= 1055$ J
$= 2.93 \times 10^{-4}$ kWh

EXPERIMENT 3. Conversion of Electrical Energy to Thermal Energy

In this experiment you will determine the electrical energy used in heating a cup of water, and you will compare this energy with the increase in thermal energy of the water.

The electrical energy provided is equal to the product of the power used and the time. Therefore, by adding a clock to the equipment used in Experiment 1, you will be able to determine the energy.

The increase in thermal energy, Q, is determined by the mass of water, m, the specific heat of water, c, and the change in temperature, ΔT.

$$Q = cm\Delta T$$

Plan your experiment. We suggest that you start with cold tap water and heat it to about 80°C, inserting the heater nearly to the bottom of the cup. Stir gently but continuously. Before beginning, note which quantities must be measured in order to calculate the electrical energy and the thermal energy.

After completing your measurements, calculate the electrical energy provided in joules and the increase in thermal energy in calories. Compare the two by applying the appropriate conversion factor. How well do they agree? What factors could cause the two values to differ?

Try the experiment with the heater on for a period of time which is different from your first trial. How does the *power* input to the water compare in each case?

Example 7. How much energy is required to raise the temperature of 10 lb of copper from 70°F to 250°F? Express the answer in Btu's, calories, joules, and kilowatt hours.
Solution: We can apply the equation

$$Q = cm\Delta T$$

Since the amount of material and the temperatures are expressed in English units, it will be convenient to do the calculation first in Btu's. Consulting the specific heat table we find the specific heat for copper.

$$\begin{aligned} Q &= (0.092 \text{ Btu/lb F}^\circ)(10 \text{ lb})(180 \text{ F}^\circ) \\ &= 166 \text{ Btu} \end{aligned}$$

Now we can use the conversion factors in Table II to express heat in other units.

$$\begin{aligned} Q &= 166 \text{ Btu } (252 \text{ cal/Btu}) \\ &= 4.18 \times 10^4 \text{ cal} \end{aligned}$$

$$\begin{aligned} Q &= 166 \text{ Btu } (1055 \text{ J/Btu}) \\ &= 1.75 \times 10^5 \text{ J} \end{aligned}$$

$$\begin{aligned} Q &= 166 \text{ Btu } (2.93 \times 10^{-2} \text{ kWh}) \\ &= 4.86 \times 10^{-2} \text{ kWh} \end{aligned}$$

Example 8a. How many calories of thermal energy are produced by a 1200-watt toaster which stays on for one minute?

Solution: In Example 4 we calculated the energy for such a case:

$$\begin{aligned} W &= Pt \\ &= (1200 \text{ W})(1 \text{ min}) \\ &= 0.02 \text{ kWh} \end{aligned}$$

Applying the conversion factor from Table II

$$W = Q = 1.72 \times 10^4 \text{ cal}$$

Example 8b. How much water can be heated from room temperature (20°C) to the boiling point (100°C) by the heat referred to in Example 8a (1.72×10^4 cal)?

Solution:

$$Q = cm\Delta T$$

$$m = \frac{Q}{c\Delta T}$$

$$= \frac{1.72 \times 10^4 \text{ cal}}{(1 \text{ cal/gC}^\circ)(80^\circ)}$$

$$= 215 \text{ g}$$

This is approximately one cup of water.

Example 9. An electric heater is imbedded in a two-kilogram piece of aluminum. The heater draws six amperes at 120 volts. If the temperature of the aluminum is initially 20°C, what will it be at the end of five minutes? (Ignore heat losses to the surroundings.)

Solution: From the information on current, voltage and time the amount of electrical energy can be calculated.

$$\begin{aligned} W &= VIt \\ &= (120 \text{ V})(6 \text{ A})(5 \text{ min}) \\ &= 3600 \text{ W}\cdot\text{min} \\ &= 216{,}000 \text{ J} \end{aligned}$$

This energy appears as heat. For determining the temperature change, it is convenient to express this energy in calories.

$$\begin{aligned} W = Q &= 216{,}000 \text{ J } (1 \text{ cal}/4.18 \text{ J}) \\ &= 51{,}600 \text{ cal} \end{aligned}$$

Now we can use the equation

$$Q = cm\Delta T$$

Solving for ΔT,

$$\begin{aligned} \Delta T &= Q/cm \\ &= \frac{(51{,}600 \text{ cal})}{(0.215 \text{ cal/gC}^\circ)(2000 \text{ g})} \\ &= 120 \text{ C}^\circ \\ T_{\text{final}} &= 20^\circ + \Delta T = 140^\circ\text{C} \end{aligned}$$

Therefore, the temperature at the end of five minutes is 140°C.

Another quantity often met in dealing with heat problems is the *heat capacity, K,* for an object. It is defined as the heat added to an object divided by the change in temperature resulting. For example, if 2000 calories changes the temperature of some object by 10 C°, the heat capacity is 2000 calories divided by 10 C°, or 200 cal/C°. Note that heat capacity is a characteristic of an *object* whereas specific heat is a characteristic of a *material.* If the heat capacity of an object is known, the heat required for a specified temperature change is readily determined:

$$Q = K\Delta T$$

Example 10. The heat capacity of a pot of beans is 1500 cal/C°. How much energy is required to raise its temperature from 20°C to 90°C?

Solution:

$$\begin{aligned} Q &= K\Delta T \\ &= (1500 \text{ cal/C}^\circ)(70 \text{ C}^\circ) \\ &= 105{,}000 \text{ cal} \end{aligned}$$

For an object made up of several materials, the heat capacity can be calculated if the amount of each material and the specific heat for each material is known. Suppose you have an object made up of three materials, a, b, and c, with masses m_a, m_b, m_c, and specific heats c_a, c_b, c_c. To produce a temperature change ΔT in material a, the amount of heat required is

$$Q_a = c_a m_a \Delta T$$

Similar expressions apply for materials b and c. The total heat needed to raise the temperature of the entire object is

$$\begin{aligned} Q &= Q_a + Q_b + Q_c \\ &= c_a m_a \Delta T + c_b m_b \Delta T + c_c m_c \Delta T \\ &= (c_a m_a + c_b m_b + c_c m_c)\Delta T \end{aligned}$$

This same total heat can be expressed in terms of K, the heat capacity:

$$Q = K\Delta T$$

Comparing the two expressions for the same quantity, we see that the following must be true:

$$K = c_a m_a + c_b m_b + c_c m_c$$

This procedure can be used no matter how many different materials are involved.

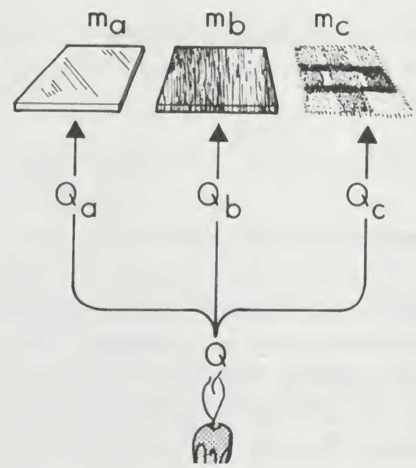


Figure 15.

EXPERIMENT 4. Heat Capacity

In this experiment you will experimentally determine the heat capacity of the toaster and will compare the result with a rough estimate based on the masses and the specific heats of the materials in the toaster.

Recall the definition of heat capacity: the heat capacity of an object is the heat required to produce some temperature change divided by that temperature change.

The amount of heat is equal to the electrical energy delivered to the toaster. It can be determined by measuring the power for the toaster and the time during which that power is applied. Since heat is customarily expressed in calories, it is appropriate to convert the energy in joules to energy in calories by applying the appropriate conversion factor.

The change in temperature can be determined by attaching a thermometer to the toaster. However, there are some complications. The heating occurs in the heating elements within the toaster, and it takes some time for this heat to be distributed so that the toaster will have a uniform temperature. (In Experiment 3 you could keep the water temperature uniform by stirring; unfortunately, you cannot stir the toaster. In fact, it takes such a long time for the toaster to heat up because it is designed not to–the bakelite handles are supposed to stay cool.) While you are waiting for a uniform temperature, there will be considerable heat loss to the surroundings. This effect can be reduced by placing an insulating box over the toaster, but the losses are still appreciable. Fortunately, there is a way to approximate the effect of these losses and adjust your data accordingly.

Suppose that you plug in the toaster, leave the power on for a minute or so, and then remove the plug. You then take and record readings of the temperature every 30 seconds, both while the power is on and for 20 to 30 minutes after the power is turned off. Don't stop until the temperature reaches the value it had when the power was turned off. If you plot these data, the graph will look like the solid line in Figure 16.

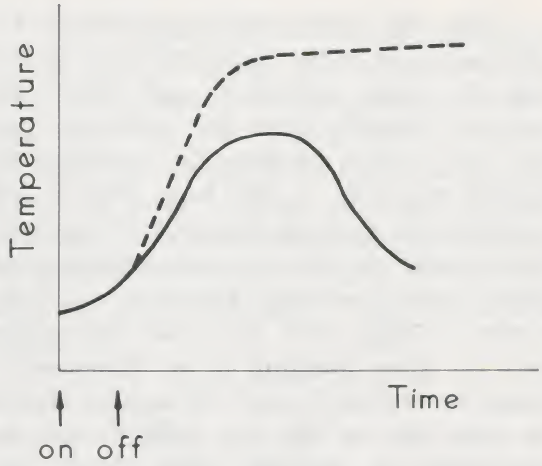


Figure 16.

The temperature will rise only slightly during the short time that the toaster is on because very little of the heat will have reached the location of the thermometer. If there were no losses, the temperature curve would follow the dotted line, approaching some final temperature as the heat gets distributed throughout the toaster. The effect of the losses is to cause the temperature to follow the solid line. By noting the temperature loss per unit time during the cooling part of the curve, you can obtain an approximate value for the temperature loss during the rising portion of the curve. To do this, follow this procedure:

1. Pick a time when the temperature of your toaster is just beginning to fall.
2. Pick a later time at which the temperature has fallen to a value equal to what it was when the power was turned off.
3. Divide the difference in temperatures by the elapsed time in minutes. The number you get is the average number of degrees the temperature fell each minute over this temperature range.
4. Multiply this number by the number of minutes the temperature of the toaster was rising. Since the toaster presumably "lost" this many degrees while it was heating, this number should be added to the total observed increase to obtain the increase we would have observed for the same energy input if there had been no heat losses to the surroundings.

With the toaster unplugged and set for light toast, attach the thermometer to its end with the tape provided, and lower the elevator. Carefully place the insulating box over the toaster, guiding the thermometer through the hole in the box. Wait a few minutes to be sure the temperature is steady. Use this time to plan your measurements and prepare your data sheet. You must record the current, voltage, and the time the toaster stays on after plugging it in. Temperature should be recorded every 30 seconds during the early part of the run. Later, when the temperature is changing more slowly, the measurements can be less frequent.

When you have finished taking data, calculate the heat capacity of the toaster from the experimental data.

For a comparison with the experimental value, a rough estimate of the specific heat can be calculated from the mass and specific heat of the materials in the toaster. To do this it helps to have the toaster partly taken apart. (Check with the instructor before doing this.) This provides you with three components whose contribution to the heat capacity can be computed separately: the steel case, the "guts," and the end caps. The mass of each of these can be determined with a beam balance.

The contribution from the steel case can be determined easily by multiplying the mass by the specific heat of steel (about 0.1 cal/gC°).

The material in the end caps is either bakelite or a similar material. If you check tables of specific heat for such materials, you find that they all have a value of about 0.5 cal/gC°. Thus the contribution from the end caps can be estimated.

The contribution from the remainder of the toaster presents a problem because there are many different materials. However, if you check the specific heat for any of the materials which appear in significant quantity, you find that they vary between 0.1 and 0.2 cal/gC°. Therefore, if you use a value of 0.15 cal/gC°, your result should be accurate to within about 25%.

From these three contributions obtain your rough estimate of the heat capacity and compare with the value determined from the heat and temperature measurement. Do they agree as well as you might expect?

Example 11. An object consists of 2 kilograms of iron, 0.6 kilograms of aluminum, and 0.4 kilograms of bakelite. What is the heat capacity of the object?

Solution:

$$\begin{aligned} K &= (0.113 \text{ cal/gC}^\circ)(2000 \text{ g}) + \\ &\quad (0.215 \text{ cal/gC}^\circ)(600 \text{ g}) + \\ &\quad (0.5 \text{ cal/gC}^\circ)(400 \text{ g}) \\ &= (226 + 129 + 200)\text{cal/C}^\circ \\ &= 555 \text{ cal/C}^\circ \end{aligned}$$

THERMAL EXPANSION

The preceding discussion has provided the basis for an understanding of the energy transformation (electrical to thermal) which occurs in the toaster. Another important feature of the toaster is the control system. What is the mechanism for shutting off the current at the right time? Could this be a simple clock timer? This might seem to be reasonable, but in actuality toasters have control systems which are based on heat and temperature, not time. To understand how this is accomplished, it is necessary to begin by studying a physical property called thermal expansion.

Have you ever noticed that electric power lines sag more in summer than in winter? This occurs because the wires expand when heated; this is called *thermal expansion.*

Experiments show that the change in length, ΔT, is proportional to the original length, L_0, and to the change in temperature, ΔT:

$$\Delta L = \alpha L_0 \Delta T$$

The constant of proportionality, α, is called the *coefficient of linear expansion* and its value depends on the material. Table III gives

the experimentally determined values of this coefficient for several materials.

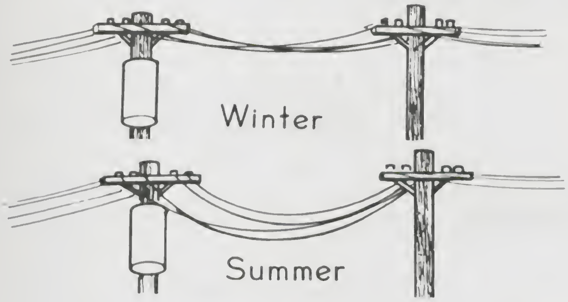


Figure 17.

Example 12. Determine the change in length of a copper wire, originally 150 feet long, if the temperature is changed from 10°F to 90°F.

Solution: From Table III, α for copper is 9.2 $\times$ 10^{-6}/F°.

$$\Delta L = \alpha L_0 \Delta T$$

$$= (9.2 \times 10^{-6}/\text{F}^\circ)(150\ \text{ft})(80\ \text{F}^\circ)$$

$$= 0.110\ \text{ft} = 1.3\ \text{in}$$

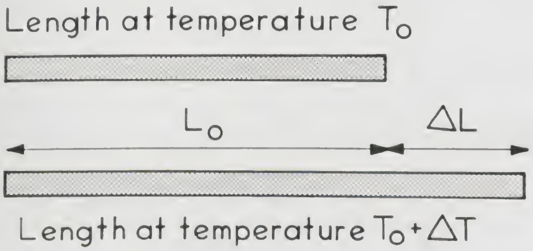


Figure 18. In this figure the amount of thermal expansion is greatly exaggerated so you can see it.

TABLE III.
Coefficients of Linear Expansion

Material	per C°	per F°
Aluminum	23×10^{-6}	13×10^{-6}
Brass	19×10^{-6}	11×10^{-6}
Glass (Pyrex)	3.2×10^{-6}	1.8×10^{-6}
Invar	0.8×10^{-6}	0.4×10^{-6}
Iron	12×10^{-6}	6.6×10^{-6}
Copper	17×10^{-6}	9.2×10^{-6}

This dependence of size on temperature can be used in devices that measure temperature and in devices that control temperature, such as the control mechanism in a toaster. Because the change in length is very small, many of these devices use two different materials in a clever way which has the effect of magnifying the movement. The arrangement is called a *bimetallic strip*, as shown in Figure 19.

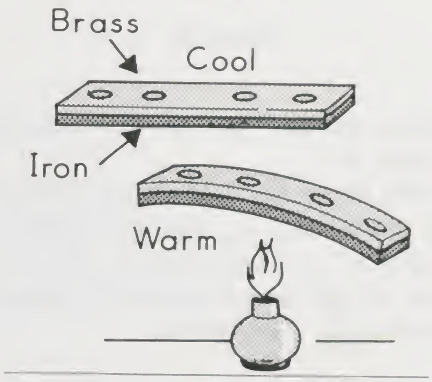


Figure 19. A bimetallic strip curves when heated.

The device consists of a thin strip of iron attached to a thin strip of brass. If the temperature of the strip is increased, both the iron and the brass will expand. However, the brass will expand about 1½ times as much as the iron because of its greater coefficient of expansion. How can the two have different lengths and still remain fastened together? The only way is for the strip to curve.

OPTIONAL DERIVATION

Figure 20 shows an idealized model of what happens when a bimetallic strip is heated. (When a scientist says "model," he means a simplified way of thinking about something complicated.) For our model we are assuming that the strip curves so that it is simply an arc of a circle whose radius is R. The angle θ is a convenient quantity to use to measure the curvature. Our task now is to predict θ; that is, to find an expression for θ in terms of the original length, L_0, the change in temperature, ΔT, the two coefficients of

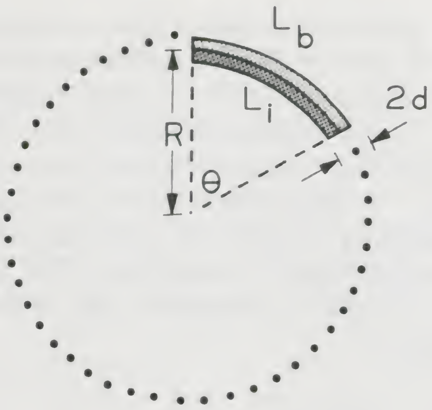


Figure 20.

expansion, α_b and α_i, and the thickness of each strip, d.

First let us find θ in terms of the length of the brass strip, L_b, and the length of the iron strip, L_i. Note that L_i is a certain fraction of the circumference of a circle; the fraction is $\frac{\theta}{360°}$. Therefore,

$$L_i = \frac{\theta}{360°} \text{ times circumference}$$

$$= \frac{\theta}{360°}\ 2\pi R$$

where R is the average radius of the iron strip. We can write down the corresponding expression for the length of the brass strip, noting that the average radius for the brass strip is greater than that for the iron by an amount equal to the thickness, d,

$$L_b = \frac{\theta}{360°}\ 2\pi(R + d)$$

Subtracting,

$$L_b - L_i = \frac{\theta}{360°}\ 2\pi(R + d) - \frac{\theta}{360°}\ 2\pi R$$

$$= \frac{\theta}{360°}\ 2\pi d$$

Solving for θ,

$$\theta = \frac{360°}{2\pi}\ \frac{L_b - L_i}{d}$$

Now we can write expressions for the lengths of the two strips in terms of their lengths when they were straight (which were equal), their coefficients of thermal expansion, and the temperature increase which caused the strips to curve.

$$L_b = L_o + \Delta L_b$$
$$= L_o + \alpha_b L_o \Delta T$$

Similarly,

$$L_i = L_o + \alpha_i L_o \Delta T$$

Subtracting,

$$L_b - L_i = \alpha_b L_o \Delta T - \alpha_i L_o \Delta T$$

$$= (\alpha_b - \alpha_i) L_o \Delta T$$

Inserting this in the expression for θ,

$$\theta = \frac{180°}{\pi}\ \frac{(\alpha_b - \alpha_i) L_o \Delta T}{d}$$

Example 13. A bimetallic strip, made of iron and brass strips each 0.01 inch thick, is straight and three inches long at 10°C. Determine the amount of curving at 80°C, by specifying θ.

Solution:

Since $(19 \times 10^{-6} - 12 \times 10^{-6}) = 7 \times 10^{-6}$

$$\theta = \frac{180°}{\pi}\ \frac{(7 \times 10^{-6}/C°)(3\text{ in})(70\text{ C°})}{0.01\text{ in}}$$

$$= \frac{(180°)(7 \times 10^{-6})(3)(70)}{\pi\,(0.01)}$$

$$= 8°$$

When designing a bimetallic strip for use in a thermometer or control device, the quantity of interest is usually the travel at the end, Δs, rather than the angle θ. We will not derive the expression for Δs, but will simply state it:

$$\Delta s = \frac{2d}{(\alpha_b - \alpha_i)\Delta T}\ \sin^2 \frac{\theta}{2}$$

Figure 21.

It is possible to write a simpler, approximate expression which can be used in most cases:

$$\Delta s = \frac{L_o^2}{2d} (\alpha_b - \alpha_i) \Delta T \qquad (1)$$

This expression is quite accurate for cases where θ is no larger than 30°, which corresponds to Δs no greater than one-fourth of L_o.

EXPERIMENT 5. The Bimetallic Strip

In this experiment you will measure the movement of the end of a bimetallic strip made of brass and invar as the temperature changes, and will compare your experimental results with the relationship introduced earlier:

$$\Delta s = \frac{L_o^2}{2d}(\alpha_b - \alpha_i)\Delta T$$

where the symbols have the following meanings:

- Δs : distance traveled by free end of strip
- L_o : Length of strip
- $2d$: thickness of strip
- α_b : coefficient of linear expansion for brass
- α_i : coefficient of linear expansion for invar
- ΔT : change in temperature

With the apparatus shown in Figure 22 you will be able to vary the temperature of the water and measure the position of the free end of the strip as a function of temperature.

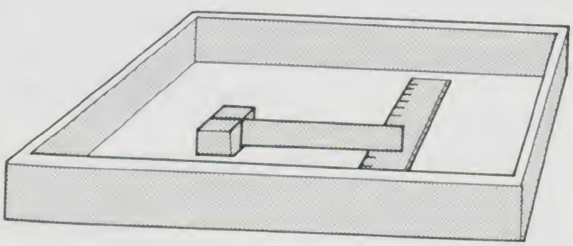


Figure 22.

Procedure:

1. Measure the length of the strip, from the scale to the point where it enters the support clamp.
2. Measure the thickness of the strip at several points and obtain the average. (Remember that this thickness is $2d$.)
3. Fill the tray with enough cold water to cover the strip.
4. Allow several minutes for the system to come to equilibrium. Then record the temperature and the position of the end of the strip.
5. Immerse the immersion heater in the water and plug it in for about two minutes. Stir gently after unplugging the heater.
6. Wait for about two minutes, while stirring, for the system to come to equilibrium. Then record the temperature and the position of the end of the strip.
7. Repeat 5 and 6 until the temperature has reached approximately 50°C.

You now have data on position versus temperature. Plot these data on a sheet of graph paper. Do the points fall approximately on a straight line? Should they, according to equation 1?

From your graph, determine the experimental value for the change in position per unit temperature, $\Delta s/\Delta T$. Using this value and equation 1, determine $\alpha_b - \alpha_i$. How well does this agree with Table III? (The agreement may not be exact because the coefficient for invar changes considerably for small changes in its composition.)

Example 14. A bimetallic strip, made of iron and brass strips each 0.01 inch thick, is straight and three inches long at 10°C. If one end is clamped in a fixed position, how much will the other end move if the temperature is increased to 80°C?

Solution:

$$\Delta s = \frac{L_o^2}{2d}(\alpha_b - \alpha_i)\Delta T$$

$$= \frac{(3\text{ in})^2}{(0.02\text{ in})}(6.6 \times 10^{-6}/\text{C}^\circ)(70\text{ C}^\circ)$$

$$= 0.21\text{ in}$$

(Since the result is much less than $L_o/4$, it is not necessary to use the more exact expression.)

THE BIMETALLIC STRIP AS A THERMOSTAT

Bimetallic strips are frequently used in electric circuits to turn the current on and off as the temperature changes. In the simplest application the purpose of a bimetallic strip is to keep the temperature constant, or static, hence the name *thermostat*.

Figure 23 illustrates a simple thermostat circuit. The insulating material in the base of the thermostat cannot conduct a current. Therefore, there will be a current in the heater only when the free end of the bimetallic strip touches the contact point at the right end. If it is touching, the heater will be on. This causes the surroundings, including the bimetallic strip, to heat up. As the strip gets hotter, it curves away from the contact point, thus breaking the circuit and turning off the heater. As the temperature goes down, the strip moves back to the contact point and the cycle repeats itself. A well-designed system of this type can hold the temperature variation to less than a degree.

In the above example the heat source is an electric heater. In a home furnace system, the thermostat circuit is used to start and stop the furnace.

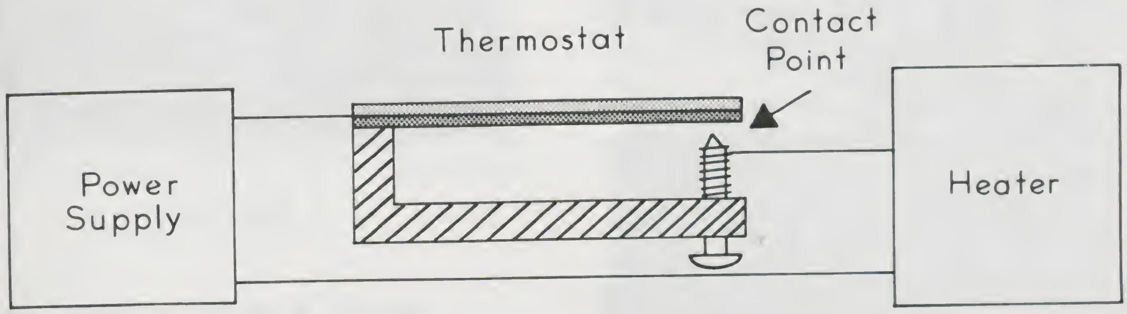


Figure 23. A simple thermostat circuit.

EXPERIMENT 6. The Toaster Control System

In this experiment you will examine the mechanism which "decides" when the toast is done and then shuts off the power and pops up the toast. Although the operation is not terribly complicated, without some guidance it would probably take you a few hours to figure it out, largely because some of the important parts and important movements are difficult to see. The suggestions below are intended to guide you through the operation in a logical order.

CAUTION: Before beginning your inspection of the system, be sure the toaster is unplugged.

Lower the elevator and note that this action closes the main switch on the toaster. See Figure 24.

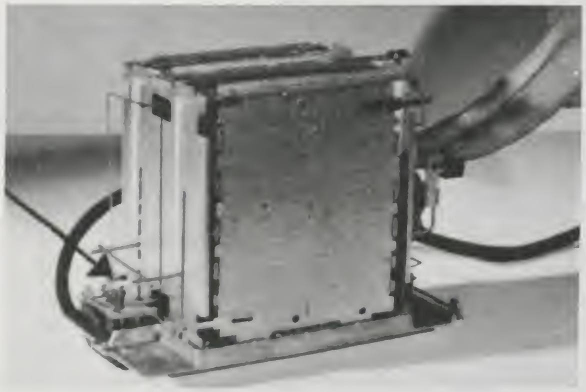


Figure 24.

With the main switch closed, current can flow in the heating elements and in the control system.

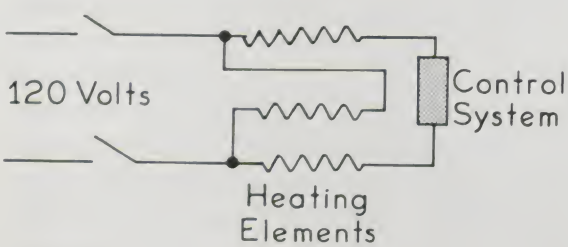


Figure 25.

It is now clear that lowering the elevator starts the cycle. What ends it? When the elevator pops up, the main switch will open, ending the cycle. Therefore, you should seek the mechanism which releases the elevator so that the spring can push it up. Note the solenoid in the photograph, Figure 26.

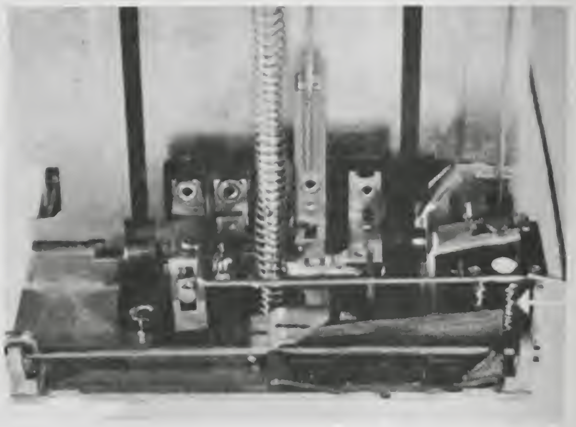


Figure 26.

A solenoid is an electromagnet which, when activated, pulls in a plunger. In the toaster, this action releases the elevator. Demonstrate this by pushing down on the plunger with your finger. The next obvious question is: what causes the solenoid to be activated? If you examine the circuit for the solenoid, you will find that the only thing preventing a current in the solenoid is the gap between the contact points indicated by the pen point in Figure 27.

The electrical hook-up for the solenoid can be represented by the schematic diagram of Figure 28.

What makes the contact points close? At this point it is valuable to see the control circuit in actual operation. In order to do this without exposing you to dangerous temperatures or dangerous voltages we have made modifications in the toaster. These modifications allow the control system to operate in its usual way, but the main heating elements are by-passed, and the voltage is reduced to a safe level.

First, be sure that the power supply is not plugged in. Your instructor will plug it in after he has checked your circuit.

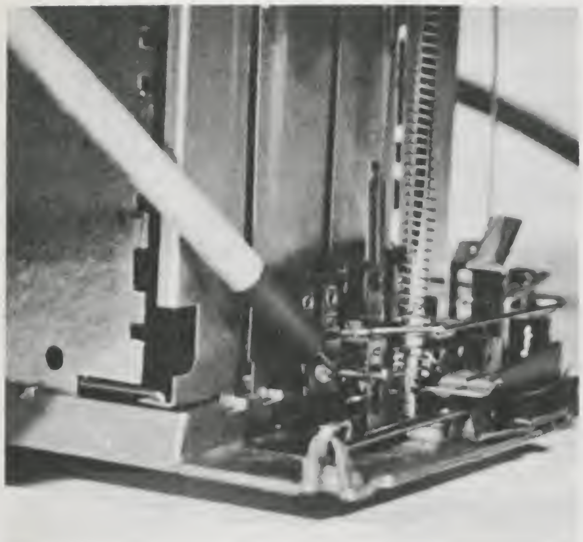


Figure 27.

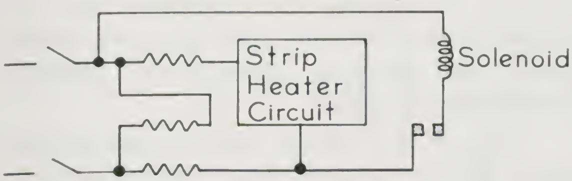


Figure 28.

Connect the toaster as indicated in Figure 29, then ask your instructor to check it.

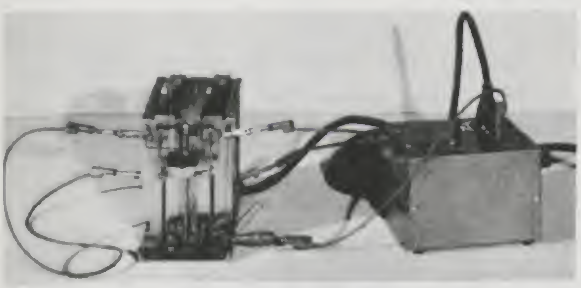


Figure 29.

Lower the elevator to start the cycle, and watch what happens. (Because of the modifications, the toaster will not get hot; otherwise, the events will be the same as in normal operation.) In particular, watch the contact points which, when closed, activate the solenoid.

What causes the motion which results in the closing of the contacts? If you suspect a bimetallic strip, you are right. What heats the strip? In Figure 30, the pen points out an insulating "stocking" which covers a small heating element wrapped around the bimetallic strip. Although the stocking hides some of the detail, you can see one end of the heating element entering the stocking. The

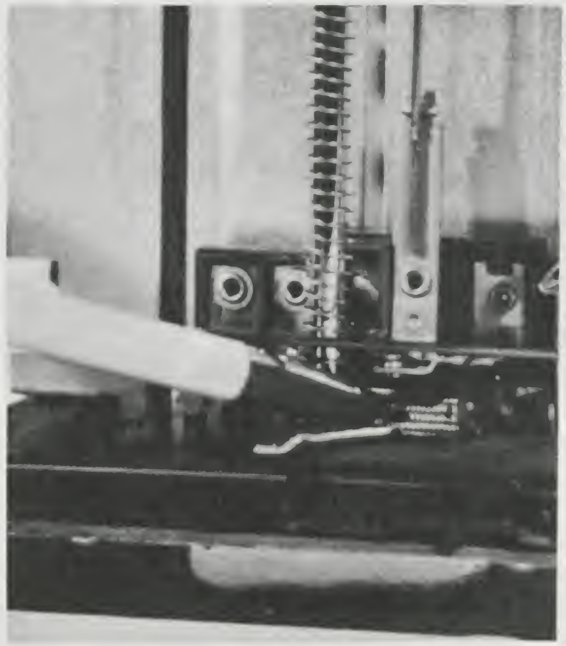


Figure 30. Heater.

other end is connected to the strip. You might think that this heater would be on all during the cycle and simply cause the strip to curve until the solenoid contacts are closed, thereby completing the cycle. However, the operation is not that simple, as you will soon discover. Try to determine the circuit for the strip heater, with particular attention to the two pairs of contact points whose location is indicated in Figure 31. (To aid in locating them, a red spot has been painted on top of one pair and a green spot on top of the other.)

The electrical hook-up for the strip heater can be represented by the schematic diagram as shown in Figure 32.

Now you should observe the motion of the strip during a complete cycle. The best view for the first part of the cycle, until you hear a click, is straight down from the top, as in Figure 33.

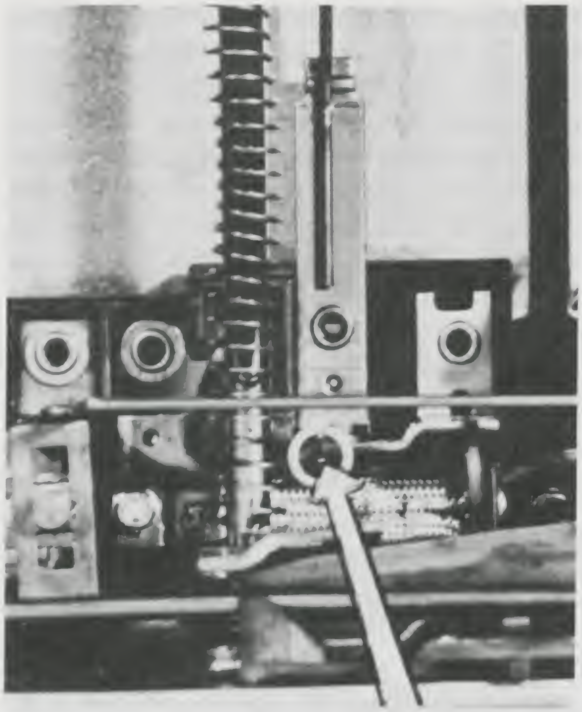


Figure 31. Contact points.

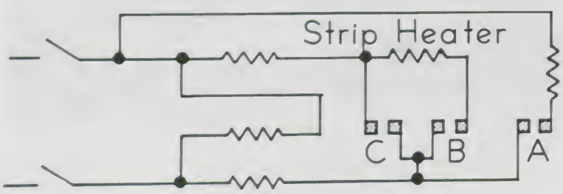


Figure 32. A: Contact points for activating solenoid.
B: Contact points which are opened to break the strip heater circuit.
C: Contact points for by-passing strip heater.

Can you figure out what is happening? You will probably want to watch through several cycles, since each cycle lasts for only about a minute.

Perhaps you noticed that during the first part of the cycle, the strip curves in such a direction that the center moves out, away from the body of the toaster. When it clears the white block (pointed out in Figure 34), it moves up. This upward motion opens one pair of contacts, breaking the circuit for the strip heater. It also closes another pair, thereby by-passing the strip heater.

With no current in the heater, the strip cools, and it begins to straighten. The block

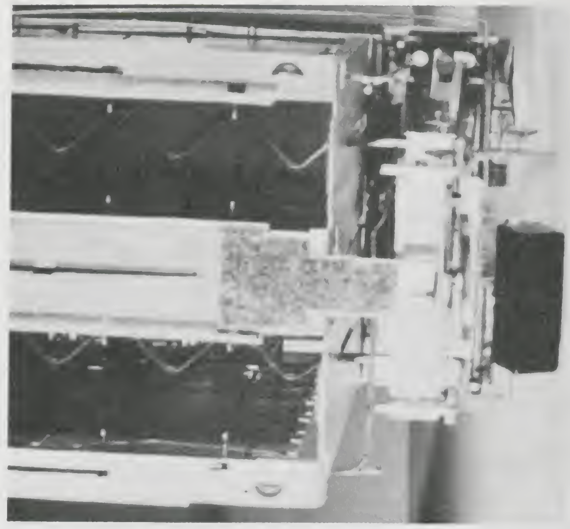


Figure 33.

prevents the center from moving back in; therefore, the free end moves out, eventually closing the solenoid contacts and thereby completing the cycle.

Why is the control system this complicated? Why not simply have the strip directly activate the solenoid and omit the part of the cycle which causes the strip heater to be by-passed? (Hint: What would happen if you tried to make a second batch of toast immediately after the first?)

Here are some other questions for you to think about:

1. During the cycle the strip clears the block and moves up. How does it get back under the block?

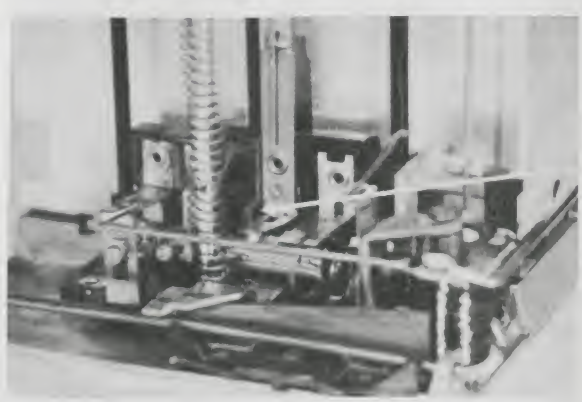


Figure 34.

2. How does the "Light-Dark" control function?
3. There are two adjustment screws near the left side of the control system. What role do they play?
4. When the elevator pops up, a wheel spins. What purpose does this wheel serve?

Example 15. In the system shown below, should the material in the top of the bimetallic strip be the one with the higher or the lower coefficient of thermal expansion? To lower the temperature in the room should the adjustment screw be moved up or down?

Answers: The material on top should have the higher coefficient of expansion. To decrease room temperature the screw should be moved up.

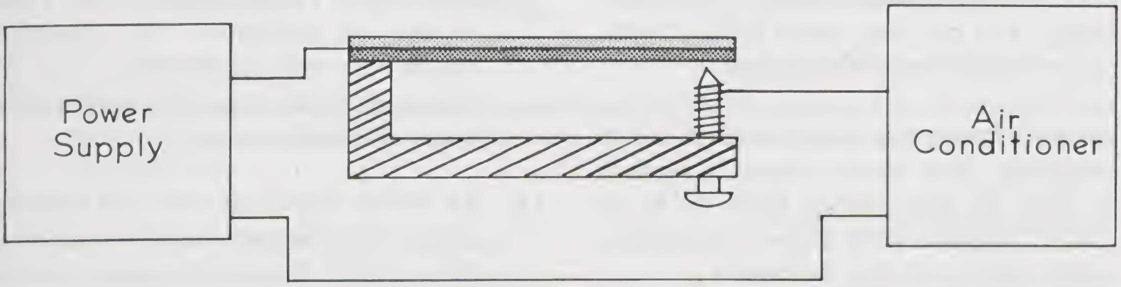


Figure 35.

SUMMARY

The transformation of electrical energy to heat energy in the toaster is an example of conservation of energy. This means that, although the form of the energy is changed, the total amount of energy is constant.

In an electric circuit, the power is the product of the voltage and the current. A unit for electric power is the watt, which is the same as a volt-ampere.

Power is the rate at which work is done, and the work done by the charges in a circuit is equal to the amount of energy delivered. Thus the energy delivered by an electric circuit is the power times the time, which is the same as the product of the voltage, the current, and the time. If the power is given in watts and the time in seconds, the energy is in units of joules. Another energy unit commonly used in connection with electrical problems is the kilowatt hour, which is simply 1000 watt hours.

The two most common units for thermal energy are the calorie and the Btu (British thermal unit). A calorie is the heat required to raise the temperature of one gram of water one centigrade degree. One Btu is the amount of heat required to raise the temperature of one pound of water one Fahrenheit degree.

Different materials need different amounts of heat to raise the temperature of equal masses by the same amount. This property is specified by stating the specific heat: the specific heat of a material is equal to the heat added to a sample of the material divided by the product of the mass of the sample and the change in temperature.

Heat capacity is a characteristic of an object, not a material. It is equal to the heat added to the object divided by the change in temperature. Its value can be calculated from the masses of the materials in the object and the specific heats of the materials.

Most materials expand when heated, but different materials expand different amounts for equal increases in temperature. Because of this, a bimetallic strip will curve when heated. This effect is used in control circuits, such as that in the toaster, to open and close electrical switches.

PROBLEMS

1. A flashlight is powered by two dry cells which provide a total of 3 volts. If the current is 5 amperes, what is the power rating, in watts, for the bulb?

2. A 300-watt heater is designed to draw 25 amperes. What is the design voltage?

3. A certain car battery has the capacity to provide 0.84 kilowatt hours of electrical energy. For how long can it run a 12-volt motor which draws 300 amperes?

4. An iron frying pan has a mass of three kilograms. How much energy is needed to raise its temperature from 20°C to 220°C? Express your answer in calories, joules, kilowatt hours, and Btu's.

5. For a particular thermos bottle, 10,000 calories are required to raise the temperature of the inside bottle from 20°C to 70°C. What is the heat capacity of the inside bottle?

6. A pound of water has an initial temperature of 176°F. What is the temperature of the water after losing 10,000 calories of thermal energy to the air?

7. A 200-watt immersion heater is used to heat an insulated container of water. The amount of water is 400 grams. Assuming that all the energy goes into heating the water, determine the rate at which the temperature increases.

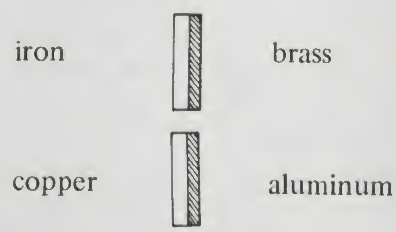
8. Determine the heat capacity of the following system: An electric skillet consisting of 1.5 kilograms of aluminum, 0.6 kilograms of glass, and 0.4 kilograms of miscellaneous materials with an effective specific heat of 0.3. Inside the skillet is a stew consisting of 2.5 kilograms of meat and vegetables having an effective specific heat of 0.8 and 1.5 kilograms of water.

9. Determine the change in length of an aluminum wire originally 200 feet long if its temperature is changed from 0°F to 100°F.

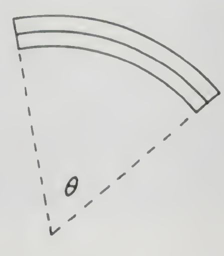
10. Suppose you have a strip of metal one meter in length. You know that it is either iron or invar. You find that when you change its temperature by 100°C its length changes by an amount somewhere between one-half and one and one-half millimeters. (Your apparatus isn't good enough to determine the change in length any more accurately.) From this information, can you decide whether the material is iron or invar?

11. An archer draws his bow and shoots an arrow into the air, nearly straight up. Discuss the forms of energy involved during the drawing, the shooting and the following motion. State which are increasing and which are decreasing during each stage of the process.

12. Decide which way each of the bimetallic strips shown will curve when heated. Indicate your answer by) or (.

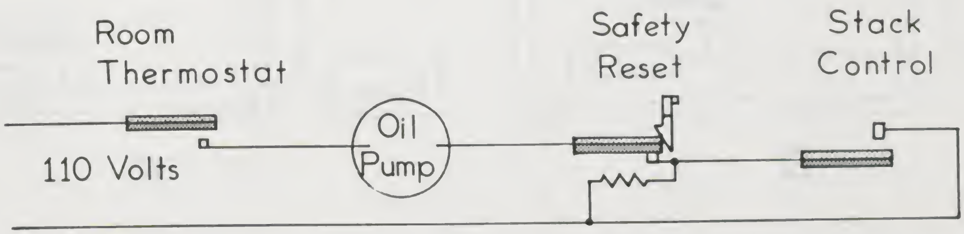


13. A bimetallic strip consisting of iron and copper strips each 0.005 inch thick and 2 inches long is straight when at a temperature of 20°C. Determine the amount of curvature at 40°C by specifying θ.



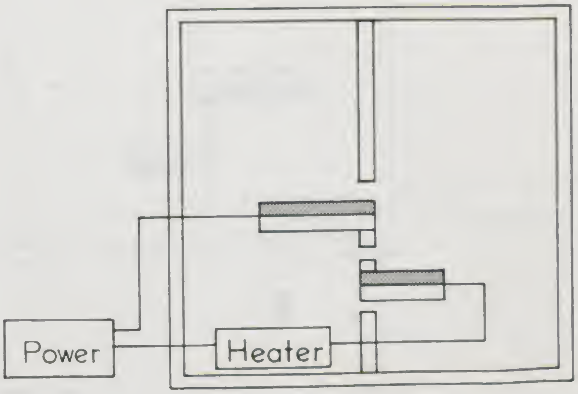
14. A bimetallic strip 2 inches long consists of brass and invar, each 0.003 inch thick. One end is clamped. Determine the movement of the free end when the temperature changes by two Fahrenheit degrees.

15. The diagram represents a simplified version of a control system for an oil-fired furnace. Explain how the system operates, including an explanation of how the stack control shuts off the oil pump if the ignition system fails.

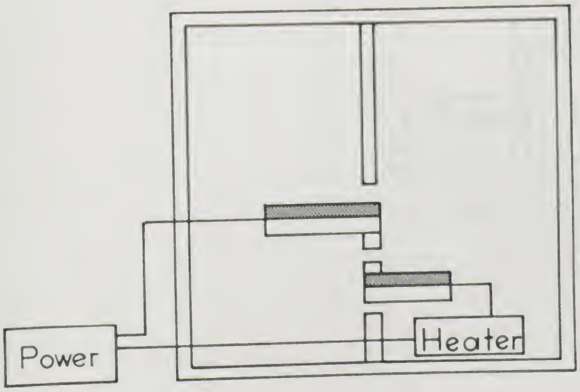


NOTE: If the fuel ignites, the heat going up the stack causes the stack control to close, shorting the heater in the safety-reset circuit. Otherwise, the safety-reset circuit will open and will be held open by the latch until manually reset.

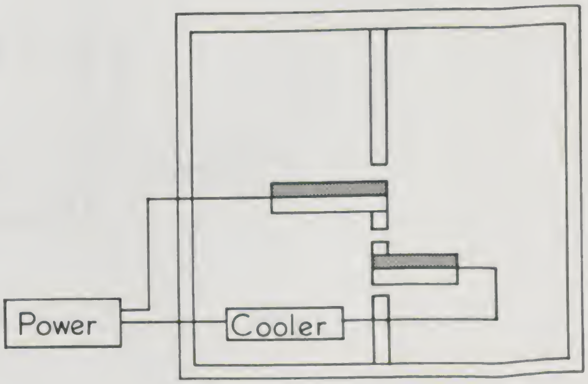
16. A container is divided into two parts by a vertical partition. A fixed temperature difference between the two parts is to be maintained by means of a control system based on bimetallic strips. In the diagrams below, the shaded part of each bimetallic strip is brass and the clear part is invar. In each case the strips make contact when they are at the same temperature. Determine which ones will produce the desired result.



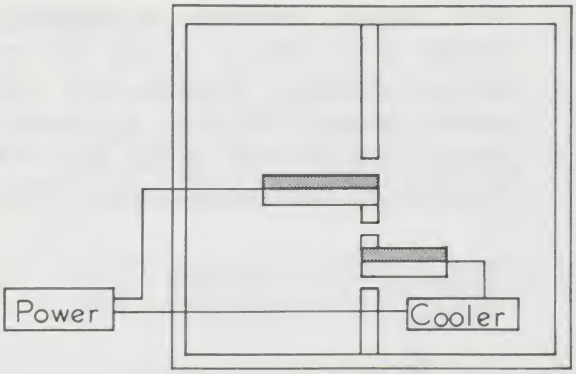
A



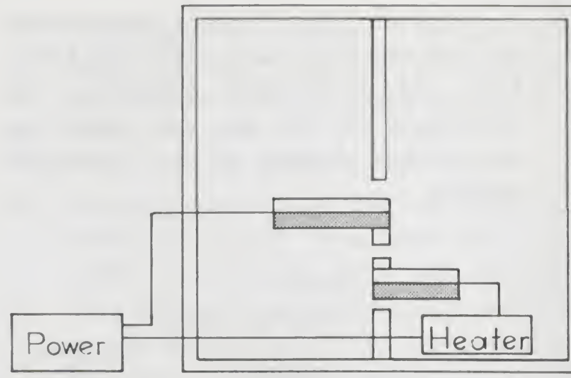
B



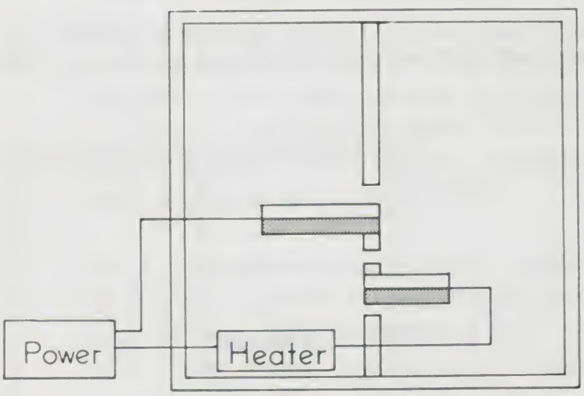
C


Power
Cooler

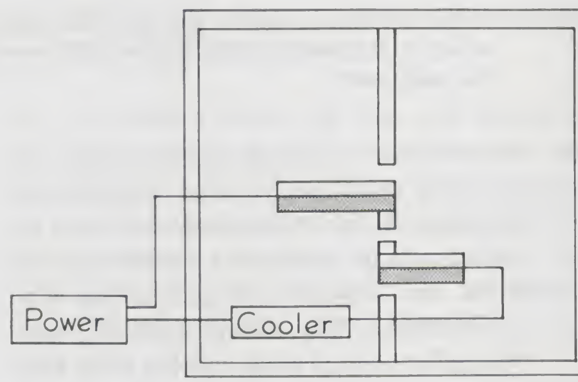
D


Power
Heater

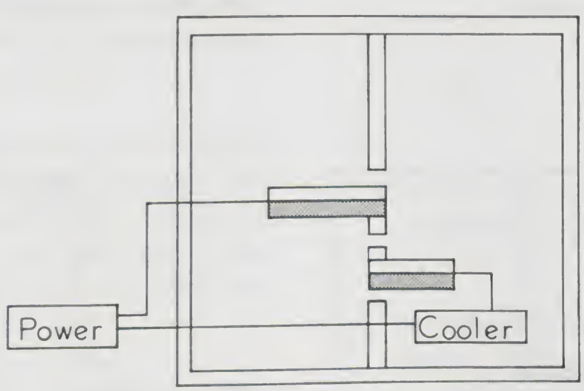
F


Power
Heater

E


Power
Cooler

G


Power
Cooler

H

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